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African women commonly carry prodigious loads (70% or more of their body weight) supported by their heads for long distances. This method of load carriage is very economical; in a comparison of the metabolic cost of carrying large head-supported loads (by African women) to large back-supported loads (by American army recruits), it was found that the army recruits had to increase their metabolism twice as much as the women for the same load at the same walking speed. The mechanism by which these women carry loads so economically is unknown. The purpose of this study was to develop a quantitative understanding of how these women are able to carry head-supported loads so cheaply.

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THE ENERGETICS AND MECHANICS OF LOAD CARRYING

FINAL REPORT

NORMAN C. HEGLUND

FEBRUARY 1, 1988 TO JANUARY 31, 1989

U.S. ARMY RESEARCH OFFICE
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Statement Of The Problem Studied.

African women commonly carry prodigious loads (70% or more of their body weight) supported by their heads for long distances. This method of load carriage is very economical; in a comparison of the metabolic cost of carrying large head-supported loads (by African women) to large backpack-supported loads (by American army recruits), it was found that the army recruits had to increase their metabolism *twice* as much as the women for the same load at the same walking speed^{1,2}. The mechanism by which these women carry loads so economically is unknown. The purpose of this study was to develop a quantitative understanding of how these women are able to carry head-supported loads so cheaply.

An understanding of the physiological and mechanical mechanisms involved in head supported load carriage requires detailed measurements of both the energy input into the system (metabolism) and the energy output (work done). Any increase in metabolism due to carrying the load (e.g. metabolism carrying load minus metabolism walking unloaded at the same speed) could be attributed to two factors: *i*) an increase in the work done; and/or *ii*) an increase in the muscular force required, even if it does not result in any work (e.g. isometric force requires metabolic energy, but no work is performed).

The work of locomotion is commonly divided into two components: that due to external forces and resulting in movements of the center of mass; and that due to internal forces and resulting in movements relative to the center of mass. Since the stride frequency of the women was unchanged by loads, the movements relative to the center of mass were unchanged, and therefore the work due to those movements would also be unchanged. On the other hand, the work due to the movements of the center of mass changes significantly with subtle changes in the movements of the center of mass (because the mass is so large) and, for the same movements of the center of mass, increases in proportion to the total mass (body plus load).

In order to measure the increase in metabolism and its two causal factors, the following experiments were planned for the University of Nairobi. First, the steady state oxygen consumption rate was to be measured in 8 African women subjects while they walked on a treadmill with and without loads at various walking speeds. The required equipment was to be supplied by the Department of Animal Physiology at the University of Nairobi. During a steady state, this measurement very accurately determines the total energy input to the system.

Second, the movements of the center of mass were to be measured using a force platform system on the same 8 subjects at a variety of speeds and with a variety of loads. The forceplate system was to be shipped to the University of Nairobi from Harvard University. This measurement very accurately determines all of the work done due to external forces during walking.

And third, muscle EMG (electromyography) activity was to be measured in various muscle groups of the neck, back and legs during some of the metabolism measurements on a treadmill (first experiments above), using EMG equipment supplied by the Electrophysiology Laboratory at the University of Nairobi. This measurement can be used as an indication of the relative force developed by the muscles at the same speed but with different loads.

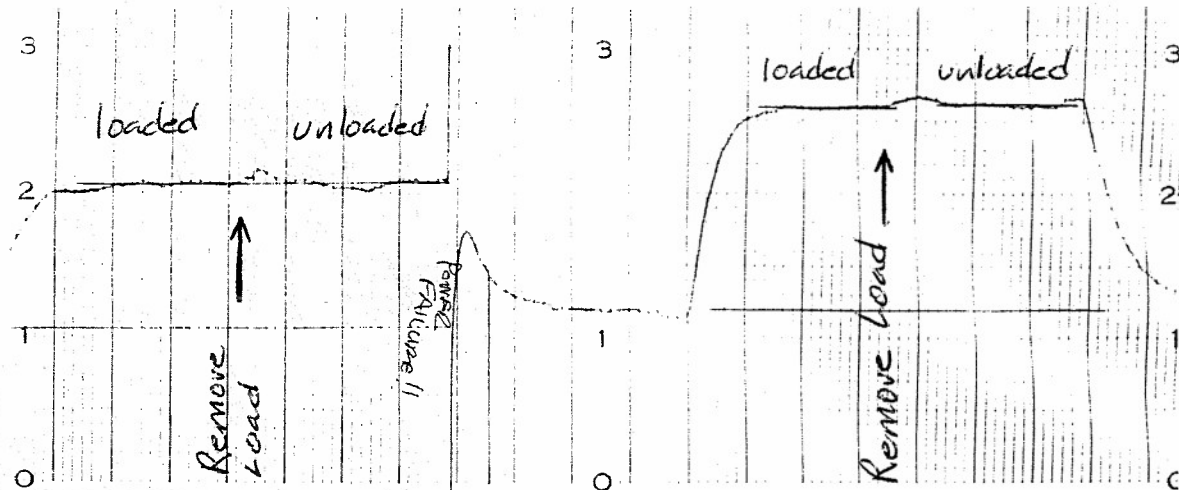
Summary Of The Most Important Results.

The metabolic studies were completed as planned, and the conclusions of our earlier metabolic studies¹ were confirmed and extended. Specifically, we was found that the

¹Maloiy, G.M.O., N.C. Heglund, L.M. Prager, G.A. Cavagna and C.R. Taylor. 1986. Energetic cost of carrying loads: have African women discovered an economic way? *Nature* 319:668-669.

²Pandolf, K.B., B. Givoni and R.F. Goldman. 1977. Predicting energy expenditure with loads while standing or walking very slowly. *J. Appl. Physiol.* 43(4):577-581.

women can carry loads of up to 25% of their body weight with *no* increase in their metabolism. For example, Figure 1 shows the oxygen consumption rate as a function of time for two different women carrying 13 kg (28 lb.) loads at 5 km/hour. The first woman was Kikuyu and supported the load with a strap across her forehead, she was considerably smaller than the other woman and the load represented 26% of her body weight. After the treadmill was turned-on, her oxygen consumption rate increased and rapidly attained a steady state; at this time the load was removed without stopping the treadmill (indicated by the arrow). After a small disturbance in the record due to removing the load 'on the fly', the oxygen consumption rate settled to exactly the same rate as when the woman was loaded. The record is then disrupted due to a power failure (a common occurrence), and then followed by the second woman.



The second woman was larger and the load represented 15% of her body weight; this woman was Luo and carried the load perched directly on top of her head. The sequence of events, and the conclusions are exactly the same: loads of 0% to 25% of body weight can be carried supported by the head free of any metabolic cost.

For loads greater than 25% of body weight, the increment in oxygen consumption rate was proportional to the increment in load (e.g. a 30% load increased the oxygen consumption rate 5%, a 40% load increased the rate 15%, and so on). The general conclusion, as stated above, is that head-supported loads during walking are far more economical than backpack-supported loads.

Unfortunately, the second experiment do not proceed as well. There were many problems that were successfully overcome in the course of the six month period of the grant, including (but not limit to) the following:

- Political problems. By chance, we arrived in Kenya immediately after student riots at the University of Nairobi which were blamed upon 'foreign political instigators masquerading as researchers'. As a result, Dr. Harry's University appointment was rescinded along with all of his benefits (e.g. housing). Dr. Harry had to work (technically) illegally at the University, and we made alternate housing plans.
- More political problems. Our local collaborator, a Principal of the University, was fired from his post shortly after we arrived, and eventually had to flee the country. With our one friend and advocate gone, we had to make new friends and alliances quickly, which we did primarily by teaching courses at the University.
- Tardiness. The required Presidential Research Permit, which Officially takes 'up to six months' to obtain, had not even arrived by the time we left Kenya, one and a half years after the application date. As a result we were subject to the whims of virtually everyone we came in contact with, and were also subject to expulsion at any time.
- Inadequate funding. Due to the lack of a Presidential Research Permit, the second funding agency supporting this research withheld its funds. Thus the only source of funds

for this project was the \$11,000 from the Army, which obviously would not even come close to covering our expenses. I was able to partially alleviate the funding shortfall by working as a consultant to the Norwegian Embassy installing a computer network in Nairobi.

These, and the many other obstacles (e.g. the University went without electricity for three straight weeks in the last month I was in Kenya), would not have stopped the research. However, the one obstacle that we were unable to work around is that Harvard University shipped to us in Nairobi one force plate (out of three) that was destroyed. Before leaving for Kenya, I tested and calibrated the plates. Apparently, after I left Harvard, someone had driven an automobile across the plate and its destruction was not noticed! In any case, to no avail we did our best to repair the plate. We were able to collect data with the two working plates (i.e. everything else was working), but due to the nature of this study, we had to have at least one complete step to do the analysis, and two plates were just not enough.

Finally, the third experiment was not successful either, although it was by far the least important of the three experiments proposed. The promised EMG equipment at the University of Nairobi turned out to be nonfunctional and so old that spare parts and repair was out of the question.

In conclusion, how these women are able to carry loads so cheaply remains a very intriguing unanswered question that is relevant to anyone who carries loads, e.g. foot soldiers in the U.S. Army.

List Of Publications And Technical Reports.

None. However, if subsequent studies result in any publications, the Army will be properly acknowledged.

List Of Participating Scientific Personnel.

Dr. Norman C. Heglund and Dr. Jason D. Harry. No training was involved in the project (i.e. no advanced degrees were earned).

Contract Number.

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